

## PROJECT GALILEO: SURVIVING IO, MEETING CASSINI

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### Abstract

Galileo has completed the long awaited Io flybys of the Galileo Europa Mission and the Galileo Millennium Mission, and is now pumping up its apojove in each succeeding orbit in preparation for the chance to perform a dual spacecraft observation of the Jupiter System. Making up for the missed opportunity at the beginning of Galileo's primary mission, a total of three close passes by Io have given us an up close and personal look at this highly volcanic body. The results presented include new and exciting information about Io's interactions with Jupiter's magnetosphere, its interior structure, and amazing volcanoes. Galileo Millennium Mission results from a magnetic field study of Europa, and its likely impact on the question of a European ocean are provided.

In addition the engineering challenges of operating the spacecraft during the past year are explored, as well as a brief examination of future challenges. The spacecraft has now experienced more than three times the radiation dose it was designed to, and this exposure is contributing to a number of spacecraft problems and concerns. The engineering data being generated by these continuing radiation-induced anomalies, and the ability of the spacecraft to survive these doses, will prove invaluable to designers of future spacecraft to Jupiter and its satellites.

### 1. Introduction

Galileo has completed its first extended mission, the GEM (Galileo Europa Mission)<sup>1</sup>, and is now partway through its second extension, the GMM (Galileo Millennium Mission)<sup>2</sup>. Figure 1 shows the trajectory of the spacecraft, both during interplanetary cruise and during the prime and extended missions. Since entering the Jupiter system in December of 1995, Galileo has racked up a total of 25 (of 27) successful encounters, exploring the four Galilean Satellites (Io, Europa, Ganymede, and Callisto); Jupiter's atmosphere, magnetosphere, and rings; and many of Jupiter's minor satellites. Figure 2 shows the details of Galileo's GEM and GMM orbits, illustrating how the flyby of one Galilean satellite targets the spacecraft for the next encounter.

Galileo closes out this latest year in triumph. As of this writing, the Galileo team has completed two (primarily) successful Io encounters (Io 24 and 25), perfect Europa 26 and Io 27 encounters, and a perfect Ganymede encounter (the first since Ganymede 8, in the Galileo Prime Mission)<sup>3</sup>. This latest Ganymede encounter sets up the spacecraft trajectory for the opportunity to conduct joint observations with the Cassini spacecraft planned at the end of this year.

Radiation exposure continues to be the prime concern, as the spacecraft has accumulated a total dose of three times the original design expectation. This has shown itself in many anomalies that have affected data return during the extended missions (See reference 2 and Sections 4 and 5). Successful completion of future encounters is not assured, as further radiation exposure will be occurring with each succeeding perijove pass, but the Galileo spacecraft has been able to survive this long.

After NASA Headquarters approved the GMM mission

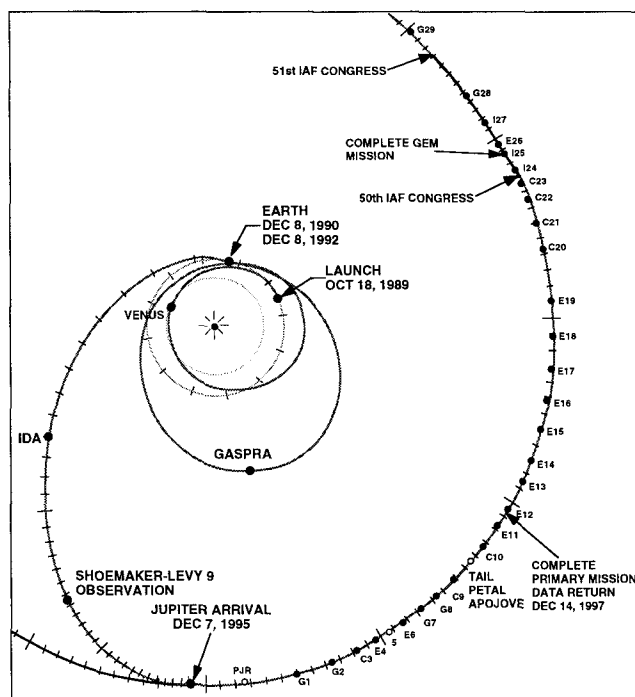


Figure 1. Heliocentric Progress

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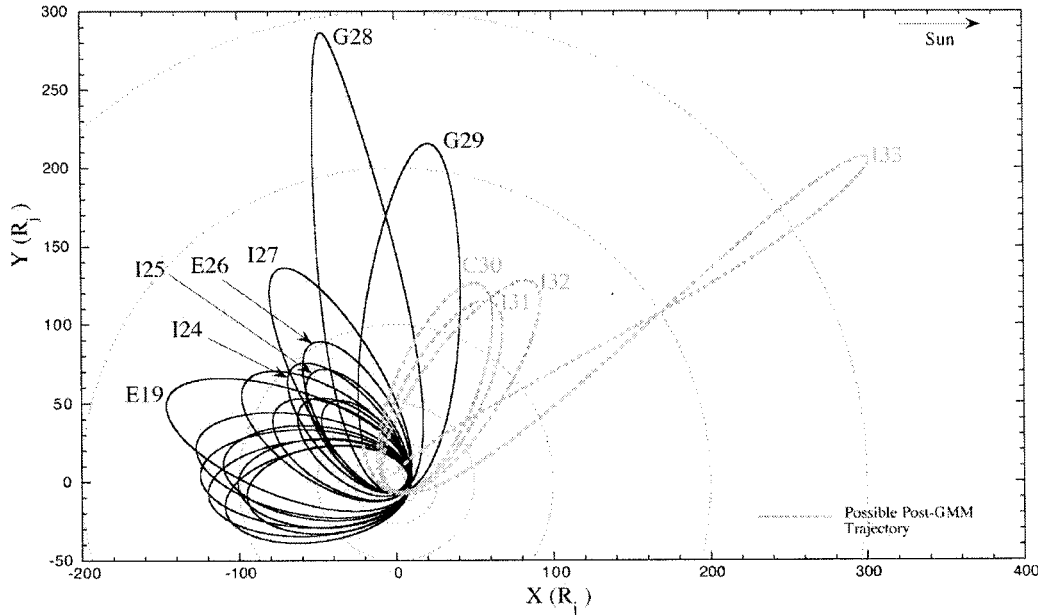


Figure 2. GEM and GMM Tour with Possible Post-GEM Trajectory

through calendar year 2000, discussions immediately began on what should be done as Galileo began to reach the end of its useful life. Discussions are underway with NASA Headquarters on a variety of possible further extensions to achieve the best science possible, and how to plan for Galileo's expected end of life. Details for one possible option are discussed in section 9.2.

As plans are beginning to be laid for the end of the mission, it is appropriate to look over Galileo's history. The first, pre-mission approval, discussions about the Jupiter Orbiter-Probe (JOP) with its plan for an atmospheric entry probe and an orbiter with an expectation of only four satellite encounters (all with Ganymede!) appeared scientifically rich and technologically challenging. The present expectation that Galileo will complete as many as thirty or more encounters covering all four Galilean satellites clearly puts the Galileo Mission into the history books as the premier voyage of discovery in the decades of the 90's and now the 2000's.

## 2. GEM to GMM Transition

The transition from the Galileo Europa Mission to the Galileo Millennium Mission was stressful, but surprisingly smooth. The activity level for the Europa 26 encounter in January was deliberately set low, both for flight team workload reasons and for the short data playback time before the Io 27 encounter in February. This allowed the operations personnel in the flight team to be heavily involved in the development of the first year's plan for the GMM. But the actual transition to the GMM began far earlier, during a Project Science Group held in August of 1998. At this meeting, the science community expressed the will that, if possible, further post-GEM spacecraft encounters should be planned to minimize the radiation dosage to allow for joint observations with the Cassini mission.

Subsequent GMM planning proceeded in parallel with the ongoing operations in the GEM. In spring and summer of 1999, the high-level science plans (an Orbit Activity Plan) for Io 24 through Ganymede 29 were developed. Between May 6 and May 31, the high-level science plan for the Ganymede 28 and 29 encounters were developed as a package. Between June 9 and August 6, the high-level science plan for the Europa 26 and Io 27 encounters were developed as a package, along with the Io 24 and Io 25 encounters. Subsequently, the Ganymede 29 science plan was revised to include the expectation that further encounters might occur in 2001 (See Section 9.2). Sequence generation for the actual commands was accomplished roughly during the 8-week period prior to their use on the spacecraft, sometimes requiring parallel development efforts to meet this timeline. As is apparent, this parallel activity, particularly during the period between October and December of 1999, placed an enormous workload on the flight team. They were able to accomplish all of the Millennium Mission planning, develop the final sequences for Io 25, and handle the Io 24 and Io 25 anomalies described in sections 4.1 and 4.2, to deliver a science rich series of encounters.

## 3. Orbiter Performance Overview

### 3.1 Attitude and Articulation Control Subsystem (AACS)

Components of the AACS hardware are showing their age and the effects of increasing radiation exposure. In addition to the gyro electronics problems (disproportionate output and maximum rate limitation) described in references 1 and 2, the primary spin detector has degraded (See Section 4.4) and the star scanner browning has increased; depending on their color, stars appear 0-20% below their nominal intensities, as seen by the star scanner.

During the peri-jove reduction phase of GEM,<sup>2</sup> at least one

AACS fault tripped in all but the final orbit (Callisto 23). This necessitated cleanup and recovery commands, as well as caused the loss of science data. To preclude further trips of these types, a decision was made to fly the Io encounters in AACS cruise mode, using only stars for celestial reference (the gyros remained off). However, the high radiation at Io's distance from Jupiter would cause most stars to be lost by the star scanner due to background radiation noise. At JOI (Jupiter Orbit Insertion) in 1995, the same problem existed, so software code enabling a single bright star to be used for celestial reference was developed. These algorithms are called OSAD (One Star Attitude Determination)<sup>5</sup>. In addition, in case the single star dropped out, a second algorithm called ASAD (Acquisition Sensor Attitude Determination)<sup>5</sup> was enabled along with OSAD. However, the low off sun angle in Io 24 (the spacecraft attitude was almost pointed at the sun) made using ASAD risky, so parameters were modified to functionally disable ASAD while OSAD was enabled. OSAD was tested in Callisto 22, and used successfully in all subsequent encounters, which were also flown in cruise mode. In Ganymede 28, a different dimmer star had to be used (Altair vs. Vega); no dropouts or misidentifications of either of these stars have been seen in any of the encounters.

### **3.2 Command and Data Subsystem (CDS) and Data Memory Subsystem (DMS)**

The spacecraft's central computer has performed well over the past year. Transient bus resets have continued but caused few problems (See Section 4.3 for more details). The tape stoppage problem seen in Callisto 22<sup>2</sup> was analyzed and found to be due to a bus reset, causing CDS to interpret a string of zeros on the bus as a spurious READY tape command. This software problem has existed since launch, but was never expressed until the bus reset auto recovery code was uploaded. A patch was developed and uplinked before the Callisto 23 sequence. However, testing of the patch revealed a problem with concurrent bus resets and tape DTRN's (DMS Turns), a sequence command used to move the tape from one track to the next. A patch to fix the DTRN problem would have been fairly extensive and could possibly cause new problems, so it was decided to work around this problem by not issuing DTRN commands while the bus reset patch is enabled.

A more serious problem was revealed just 19 hours before the Io 24 closest approach; a stuck bit in CDS memory was detected by an onboard fault monitor, triggering a fault protection routine that cancels the stored sequence and turns off nonessential loads. This sequence of events is known as "safing" or "safe mode." This Io 24 problem also indirectly led to a safing in Io 25 (See Sections 4.1 and 4.2 for more details). The only previous CDS memory failure occurred in 1994; two failures in 10 years is less than had been predicted pre-launch.

The DMS tape recorder continues to function nominally, even though the number of start/stop cycles already exceeded

the lifetime specification after the prime mission ended in 1998. An end-to-end tape conditioning is performed every 30 days.

### **3.3 Power/Pyrotechnic Subsystem (PPS)**

The RTG (Radioisotope Thermoelectric Generator) output has continued to decay per prediction (about 7 Watts a year), dropping to 454 Watts in July 2000. The power management strategy was changed in Europa 26 to accommodate the loss of power; the spacecraft no longer cycles the photometric calibration target (PCT) heaters from encounter to cruise phase. The result of having the PCT heaters off during thruster firing events is to allow contaminants to remain on the target, slightly degrading calibration data.

In future orbits, heaters will need to be cycled during encounter high-speed data recording to ensure a sufficient power margin. There are also restrictions on when the EUV instrument is allowed to operate.

### **3.4 Rocket-Propulsion Module (RPM)**

The RPM subsystem has continued to perform well, completing all scheduled thruster maintenance activities, spacecraft attitude turns, spin rate corrections, and orbit trim maneuvers (OTMs). From September 20, 1999 through May 31, 2000 the spacecraft performed 16 OTM's (OTM-73 through OTM-88) to stay on the designed trajectory. Normally, three maneuvers are performed per orbit; in both the Io 24 and Io 25 orbits, four maneuvers were planned for and performed. In each case, the apojove OTM was larger than those routinely performed, and if not executed close to nominally, the cost to propellant margin would have been too high. The solution was to add a fourth OTM to serve as a cleanup maneuver shortly after the apojove OTM. In particular, the Io 25 apojove OTM (OTM-79) was 21.6 m/s of Delta-V and consumed 11.4 kg of propellant, ten times larger than most GEM OTM's. A nonstandard sequencing method had to be developed for this maneuver, as it required more memory than is reserved for an OTM. OTM-79 was performed over a 22-hour period on 14 Nov 99, and executed within 1.3% of its design.

The propellant margin at the end of Ganymede 29 is currently predicted to be 12 kg, with sufficient propellant remaining to complete the proposed extended tour through I33.

### **3.5 Temperature Control Subsystem**

Several instruments and electronics bays utilize Radioisotope Heater Units (RHUs), which provide 1W of heat at beginning of life and slowly degrade over time. Ten years after launch, some instruments are running lower in temperature due to degrading RHUs, but all (except the magnetometer sensors) are operating comfortably above their operating limits. Thermal cycles on the CDS electronics in Bay A are kept to a minimum by sequencing design. The CDS electronics Bay A is holding steady at 7.8°C, which is above its lower

operating limit of 5°C. Due to decreasing power margin, no heaters are currently being used to raise the Bay A temperature.

### 3.6 Telecommunications Subsystem

The communications link between Galileo and Earth remains healthy. The USO (ultra stable oscillator) frequency and VCO (voltage controlled oscillator) voltage continue to drift, likely due to radiation degradation and time. A 21-day conjunction period of no expected communications with Earth due to solar interference was completed nominally; only 12 days passed without any spacecraft contact.

## 4. Non-Instrument Anomalies

### 4.1 Bad Memory Cell Anomaly

The spacecraft entered safe mode in Io 24 due to a CDS memory cell failure, in which one bit in the B side memory was stuck on “1”. The timing of the fault helped point the general location of the failure in CDS memory to a shared buffer location used for SSI playback and PPR/NIMS recorded data processing. Since none of these processes had been used since just before the Callisto 23 encounter, the memory cell failure could have occurred months before the spacecraft safing. Fortunately, the Io 24 sequence could be modified to not invoke those modes (See Section 6 for more details). After the encounter, a series of real-time commands were developed and sent to carefully pinpoint the exact location of the bad cell. Fortunately, the SSI playback buffer did not overlap the bad cell, and so SSI playback could be initiated. A patch was developed to move the PPR data buffer off of the bad cell location, and was uplinked before the Io 25 encounter. This patch involved moving the B-side PPR buffer down into former sequence memory area, which is partitioned into 5 boxes. To make room for the PPR buffer, each B side box was made slightly smaller, and the fifth box was moved to a new location. (See Figure 3). Unfortunately, another “present since launch” software bug interacted with this patch to cause the Io 25 spacecraft safing, as discussed in the next section. A separate patch to move the NIMS data buffer off of the bad cell location was developed for the Ganymede 28 encounter; however, testing revealed an unexpected interaction with other software, and this patch is being revised. It is currently expected to be loaded for the Ganymede 29 encounter.

### 4.2 Memory Addressing Anomaly

Command sequences are loaded into temporary memory and then moved into the main memory area in box-sized chunks as space becomes available. The PPR data buffer patch moved the location of the B side box 5 (See Figure 3). During Io 25 encounter operations, when the spacecraft autonomously loaded part of the command sequence into the box on the B side, the spacecraft entered its safe mode. Analysis showed that the new box 5 memory area was still write-protected (privileged memory), due to a code problem present since launch in which the B side referenced the A-

side’s write protection parameters. As command sequences are always smaller on the B side than the A side, it was simpler to work around this problem by only using four B side boxes than to devise a fix.

### 4.3 Transient Bus Reset Anomalies

Transient bus resets continue to occur up to several times each encounter, presumably induced by radiation exposure. The number of bus resets experienced in recent encounters is/ are: Callisto 22—three, Callisto 23—one, Io 24 —one, Io 25—two, Europa 26—two, Io 27—three, Ganymede 28—two. More bus resets occur while outbound from Jupiter, rather than inbound. A flight software patch loaded after Europa 19 allows the spacecraft to recognize a bus reset and not enter safe mode.<sup>2</sup> Standard sequencing procedure has been to enable the patch while within 15 R<sub>J</sub> (Jupiter radii, 1 R<sub>J</sub> = 71,492 km ) of Jupiter at a minimum, or at least 24 hours before the start of the encounter sequence. The patch cannot be enabled while playback of DMS data is being performed; 15 R<sub>J</sub> allowed protection against the most intense radiation while not delaying playback initiation in most cases. In Io 27, a bus reset unexpectedly occurred at 29 R<sub>J</sub> outbound, resulting in a spacecraft safing since the patch had already been disabled. In Ganymede 28, due to conjunction and the extended fields and particles data plan (See Section 7.5), it was possible to enable the patch well before Jupiter and leave it enabled well past encounter. The decision for when to have the patch enabled in future orbits has not yet been made.

### 4.4 Spin Detector Anomaly

In the Callisto 22 encounter, the spin detector caused an AACS fault trip, turning off the spin detector. When re-enabled after encounter, the same fault condition reoccurred.

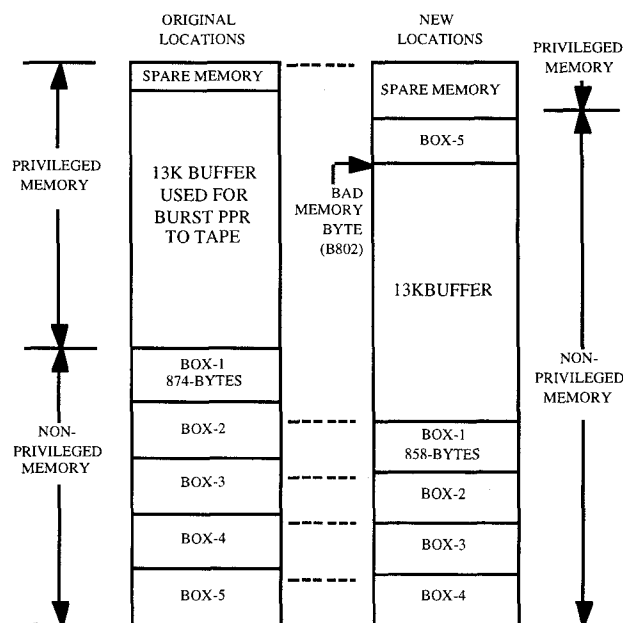


Figure 3. Relocation of 13K Buffer—B Side

The spin detector's output was found to be unreliable, likely due to radiation degradation. While a second spin detector resides onboard, it has never been used in flight and would require a lengthy calibration process, assuming it has not degraded as well. The original purpose of the spin detector was to provide a reliable spin source when Galileo was nearly sun-pointed and stars were not available as a reference source. The only time this is a concern is during OSAD encounter operations, in case the star is lost by the star scanner or misidentified due to background radiation. To provide a spin source in such cases, several AACCS parameters were changed to force the spin detector to output a constant value. The forced-output spin detector is only used during OSAD operations, and disabled otherwise. The commanded value is updated for each encounter based on the current spacecraft spin rate.

#### 4.5 Gyro Degradation

As described in references 1 and 2, the gyro electronics have two problems—disproportionate output, and a maximum operating rate. Flying all encounters in cruise mode/gyros off eliminates the maximum rate problem. However, the gyros have continued their pattern of degrading further during encounter and annealing slightly afterwards, as shown in Figure 4. Gyro tests are performed twice per orbit to characterize the degradation so that updated scale factors can be uplinked to the spacecraft to compensate. Gyro output is required to be within a certain accuracy for large OTMs and spacecraft turns.

### 5. Instrument Status

The past year has seen the failure of one of Galileo's remote sensing instruments, and significant anomalies resulting in some decrease in capability in two others.

The UVS instrument is no longer being operated. The

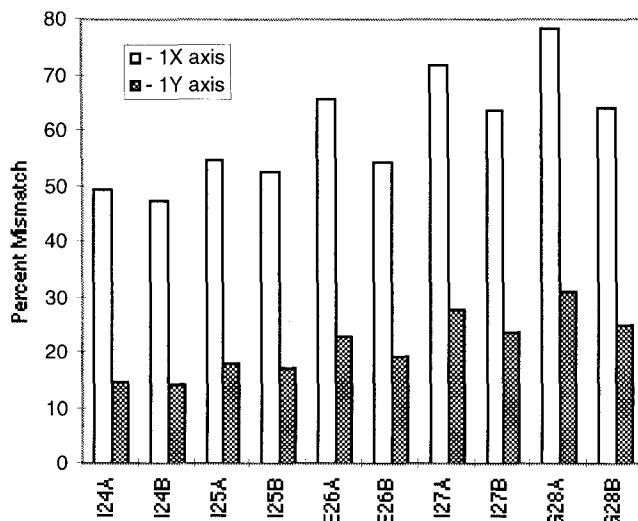


Figure 4. Gyro Degradation

grating drive encoder mechanism does not respond to microprocessor commands, and no valid spectra can be collected by the instrument. The failure occurred gradually—in retrospect, some early symptoms may have been manifested during prime mission. Callisto 20 data was partly corrupted due to the grating, and Callisto 22 data indicated nearly complete failure of the grating. Attempts to fix the instrument prior to Io 24 included an instrument cold start, a switch to the backup grating drive encoder, and memory reloads. During Io 24 cruise, modifications to UVS flight software were made to try to control the grating. In subsequent orbits, the instrument was left powered down and tests were performed to see if any annealing occurred in the encoder electronics, “healing” some of the hypothesized radiation damage. Although possible evidence of minor annealing was seen, none of these actions restored the instrument to operational status. It is surmised that long-term radiation exposure affected the sensitivity of the encoder mechanism, but mechanical wear or other failure scenarios cannot be ruled out.

The NIMS instrument, which saw two of its 17 detectors fail during the prime mission, experienced a failure of its grating sometime between Callisto 22 and Io 24 (the instrument made no observations in Callisto 23). The grating is stuck in a fixed position rather than moving as commanded. NIMS continues to return high resolution thermal and some specific types of compositional maps of the Galilean moons, and can still address most of its objectives for Jupiter atmosphere observations. However, spectral bands in between the currently available 15 bandpasses can no longer be obtained, ruling out some types of quantitative spectral measurements. Several attempts were made to diagnose and fix the grating, including grating tests and power cycles during Io 24 cruise, and instrument heating cycles during the cruise period of Io 25 and Europa 26. No changes to the grating behavior were observed. In addition, NIMS continues to experience periodic software halts, but sequenced memory reloads have been extremely successful in preventing loss of data due to these halts.

The SSI instrument has experienced data corruption in two of its 7 available record modes. During Callisto 22 observations, most HIS mode data was found to be corrupted, although in a relatively benign manner. During Io 24, significant to complete corruption was observed in the majority of Io 24 images obtained in AI8 mode (See Section 7.1 for more details). Neither mode has been used since the corruption was found, except for a test image obtained in HIS mode during Ganymede 28. The data from the test is yet to be played back off the tape recorder. Both of the affected modes employ hardware (in camera) averaging of a 2x2 block of pixels; thus, loss of these modes means fewer images per orbit can be recorded and/or returned, but those non-summation mode images are at twice the summation mode resolution. The favored hypothesis for the source of this problem is that the summing routine is executing improperly because of radiation damage and/or interference which causes timing problems within the camera circuitry. It is not known if corruption

would occur at low radiation levels (i.e., far from Jupiter). Most of the corrupted Io 24 images were reconstructed on the ground and provide scientifically usable data (See Section 7.1). During Ganymede 28 cruise, SSI experienced an anomaly in which the instrument drew 28 milliamps more current and the baseline stabilization voltage increased, likely involving the camera light flood becoming stuck “on”; a command to turn off the light flood returned the current and voltage to the nominal levels. Analysis of this anomaly is ongoing.

The EPD instrument continues to experience transient problems. During Callisto 22 cruise, the instrument high voltage cycled off unexpectedly. During the Io 25 encounter, prior to both Io closest approach and the safing event, EPD temperatures dropped unexpectedly. Commands were issued to power the instrument off and power on replacement heaters in order to return to a thermally safe state. This subsequently required a complete EPD software reload. Just after the Europa 26 encounter, EPD temperatures again began to drop and a memory reload was required during the cruise period. During the Io 27 encounter the instrument stopped producing data packets unexpectedly. Fortunately, this occurred after the Io 27 closest approach period. Recovery included a power cycle and instrument reload. A sequenced memory reload was placed after Ganymede 28 encounter to minimize possible real time recovery efforts; it was not needed. Although aspects of these anomalies are similar, no single cause has been found that explains all of them.

The PPR instrument has operated nominally, showing no recurrence of previous problems such as filter wheel sticks or the unexplained cessation of radiometer function during Callisto 20. PLS continues to show no counts in two of its seven electron detectors, while PWS’s low frequency search coil continues to be nonoperational. Neither of these instruments, nor DDS, EUV, HIC, or MAG have experienced any anomalies during the past year; all continue to function nominally. The DDS channeltron voltage has been increased from its nominal setting in GEM (1040 V) by three steps over the past eight months to 1390 V. This was done in order to compensate for decreased sensitivity caused by detector seasoning.

## **6. Sequence Operations in GEM/GMM**

Preparation for ground response to spacecraft problems during encounters became a major focus of Sequence Operations this year, as the likelihood of radiation induced errors increased with each passage through the charged particle environment near Jupiter. The process of recovering the spacecraft from a safe mode typically consists of three steps: immediate or near-term commanding to diagnose the problem and establish spacecraft health; restore standard spacecraft configuration and operational mode; and restart the planned sequence of science and engineering activities. Each recovery effort is customized taking into account the specific fault indication, risk management, criticality of upcoming events,

and available time and resources. Out of experience, necessity, and a strong motivation on the part of the flight team to achieve the Io science missed in 1995, preparation for anomaly recovery was expanded as compared to last year<sup>2</sup> by pre-building contingency science sequences.

The first two steps, problem diagnosis and spacecraft recovery, are done using a library of pre-reviewed commands to read out diagnostic registers, clear fault flags, and restore spacecraft state and functionality. Having pre-generated individual and grouped commands provides flexibility while minimizing the effort in real-time to build and validate non-standard command packages. The library of “off-the-shelf” commands and command sequences was started in prime mission and has grown through each GEM experience and change in spacecraft capability.

The third step of the recovery process is to restart nominal operations with a stored sequence of commands performing both science observations and supporting engineering activities for days to weeks.<sup>1</sup> At least two requirements are placed on these sequences which limit the amount of work that can be done up front: they must have a guaranteed start time after completion of the other two recovery steps, including enough time to send the modified sequence to the spacecraft, and they should not contain activities that would trigger the same fault.

The high priority of Io science (and the incentive that each flyby could be the last) led to the development of contingency science sequences as part of the preparation for encounters. The nature of the Io encounters, where the bulk of data recording is confined to short periods of time around closest approach, offered clearly defined restart points for these sequences. Initial conditions such as tape recorder and scan platform position, downlink mode, and instrument configuration are well defined at the restart points and can be matched either by real-time commands or by building set-up commands into the sequence itself. Because the contingency sequence is built from the nominal sequence, most of the science observations remain intact, already checked for constraint violations. In the event of an anomaly, the contingency sequence is quickly evaluated for conflict with the suspected fault and for feasibility of meeting the start time. If necessary, minimal changes are made and reviewed by instrument and subsystem representatives.

Limited insight gained from routine telemetry, supplemented by diagnostic read outs from CDS and AACS memory, provides the basis for trading the risk of recovering the spacecraft without further investigation against the loss of mission objectives, especially during encounters. Descriptions of the Io 24, Io 25, and Io 27 safe mode recoveries given below illustrate different risk trades.

Approximately 19 hours before Io 24 closest approach, safe mode was detected with initial indications that one side of the CDS had gone down. Recovery followed standard practice and involved bringing the string back up, restarting the science processor, repositioning the tape recorder, and loading a contingency science sequence. The pre-selected sequence

restart point was about one and a half hours before Io closest approach and allowed time to reconfigure some of the instruments before the start of data recording. Based on telemetry, the fault was determined to be a memory read error in the CDS B string executive controller (See Section 4.1). This implied a memory error, either transient or permanent. Because the error was detected by the CDS bus controller and not the microprocessor, it was likely to be in memory used for data buffers. The timing of the fault correlated with PPR data collection and implicated an area of memory used to buffer science data for specific PPR and NIMS record modes and SSI playback.

Based on this preliminary assessment, the decision was made to proceed with the recovery process with the objective of salvaging as much of the encounter science as possible. The contingency science sequence was reviewed and all stand-alone PPR observations were deleted (See Section 7.1). The NIMS recordings did not use the buffer and were retained. Concurrent with the effort to modify the contingency sequence, a different group continued analyzing the problem, recovering the spacecraft to its standard operating state and matching the initial conditions expected by the science sequence. Over 6 hours were eliminated in the recovery timeline by sending only those read out commands essential for verifying critical recovery steps and by utilizing autonomous checking built into the recovery command packages to reduce the need for ground verification. Subsequent to recovering the encounter, the playback plan was changed to avoid SSI data return until the exact location of the memory error could be identified and to remove processing instructions pertaining to observations that were lost between the safing event and start of the contingency science sequence.

At Io 25, safe mode was detected slightly less than four hours from Io closest approach which, with a 34-minute one-way-light-time, meant a total of three and a half hours to respond in order to recover one of the remaining two tape recorder tracks of Io data. Because several key positions were staffed to monitor the encounter, critical diagnoses and planning could be done while a full team was assembled. Preliminary analysis of telemetry did not identify the fault; however, relying on engineering judgment that the recovery commanding would not put the spacecraft hardware at further risk a decision was made to proceed with a bare-bones accelerated recovery. In the worst case, safe mode would be invoked again. Because both CDS strings were still operating, the recovery process consisted of restarting the science processor, repositioning the tape recorder, and loading a modified science sequence. With such a short recovery time, the pre-generated contingency sequence had to be truncated at both the front and back ends to match a new restart point and to reduce the amount of time required to load it onboard the spacecraft. The recovery process completed with about 4 minutes to spare before the modified sequence went active. A second sequence was generated and loaded about eight hours later to perform the necessary functions for the following two weeks until the

scheduled start of the next standard sequence.

Io 27 recovery was completely different because the fault occurred near the end of encounter (See Section 4.3) after most of the science data had been collected. Telemetry indicated it was a routine bus reset and a standard recovery process was followed. The contingency sequence was not used since the fault occurred late in the encounter; however, the following cruise sequence was truncated to start a day and a half later.

The experience with Io 24 and Io 25 highlighted that the time required to uplink a new science sequence places constraints on recovery time. Efforts to mitigate this constraint resulted in alternative strategies being implemented for Europa 26 and Ganymede 28. For the highly focused Europa 26 encounter, the contingency sequence was small enough to fit in the area of CDS memory used for maneuvers. It was pre-loaded before the encounter and would have been activated by command from the ground, if needed. For Ganymede 28, an even more sophisticated method to jump start the nominal sequence rather than reloading a modified sequence was planned and tested. Because both encounters executed flawlessly, neither technique was exercised.

## **7. Summary of Encounters in the Past Year**

### **7.1 Io 24**

Although Galileo had flown by Io in late 1995, only the fields and particles instruments (DDS, EPD, HIC, MAG, PLS, and PWS) obtained data during the flyby. Remote sensing observations were excluded because of concerns regarding the operation of the tape recorder, which had experienced a major anomaly. Low-rate (7.68 kbps), continuous recording was thought to be safe, allowing data from the atmospheric probe and from the fields and particles instruments to be obtained. Recording of remote sensing data required both higher rates and discontinuous tape motion and was therefore excluded from the Jupiter approach sequences.<sup>6</sup>

It was therefore with a considerable sense of excitement that the Flight team approached the Io 24 encounter, which marked the beginning of the Io Phase of the GEM. Distinct from the Europa Phase (orbits Europa 12 through 19) and the Perijove Reduction Phase (orbits Callisto 20 through 23), this portion of the mission focused observations almost exclusively on objectives pertaining to the geology and geophysics of Io and the interactions between the innermost Galilean satellite and the Jovian magnetosphere. The primary science objectives in this phase include:

- Studies of the surface and transient atmosphere of Io, including studies of volcanism and volcanic landforms, surface composition, and surface thermal properties.
- Studies which lead to a better understanding of Io's interior, including measurement of Io's gravity field (for moment of inertia), attempts to determine the presence or absence of an internally-generated magnetic field.

- Studies which characterize the electromagnetic and radiation environments within the Io torus region, as well as the interaction between the torus, Io itself, and the Jovian magnetosphere.

To meet these objectives, observation strategies similar to those used throughout Galileo's Prime Mission and GEM were utilized during the Io 24 encounter. Remote sensing instruments were to obtain UV, visible, and infrared images and spectra of Io's surface features, atmosphere, and volcanic plumes. UV and EUV spectra were to be obtained of the Io torus (Note that UVS was not operational—See Section 5). Doppler tracking of the Galileo spacecraft during the 24 hours on either side of Io closest approach would be used to refine estimates of Io's gravity field and internal structure. Both real-time science (RTS) and recorded fields and particles data would be gathered during passage through the Io torus region and during a 1 - 1.5 hour period near closest approach to Io.

The first Io encounter and the thirteenth satellite encounter of the Galileo Europa Mission occurred on October 11<sup>th</sup>, 1999, 04:33 UTC at an altitude of 612 km. The encounter sequence was designed to be just under four days in duration, beginning at 04:00 UTC on October 10<sup>th</sup> and ending at 03:00 UTC on October 14<sup>th</sup>. Figures 5a and 5b illustrate the timing and location of many of the encounter observations relative to Galileo's trajectory. During the encounter with Io itself, the spacecraft approached Io on its night side and upstream relative to Io's magnetospheric wake. A magnetospheric wake is created by the flow of plasma that co-rotates with Jupiter's magnetic field and sweeps past the satellite. Galileo reached the closest approach point directly above 4° N, 224° W shortly after the Sun had risen on Io's surface.

The encounter sequence began with the start of acquisition of low-rate, real-time magnetospheric data by the six fields and particles instruments. Such RTS data are obtained in all GEM orbits for periods of 2-4 days centered on perijove, in order to monitor the behavior of the inner magnetosphere of Jupiter and provide context for any high-rate, recorded data. This survey of the inner magnetosphere began with the encounter sequence, at 16  $R_J$  (Jupiter radii; 1  $R_J$  = 71,492 km), and was to continue until 06:00 UTC, Oct. 12<sup>th</sup>, at ~15  $R_J$  outbound.

More than a day prior to the start of the encounter sequence, the dust detector instrument (DDS) began collecting RTS data on its own. The ability of DDS to detect dust emanating from the Jovian system is a function of the relative geometry of the spacecraft (and thus DDS) and Jupiter. For this encounter, DDS began obtaining data on Oct. 8<sup>th</sup> at 21:30 UTC, and planned to continue through 02:00 UTC on Oct. 22<sup>nd</sup>.

A PPR calibration and an observation of wave structures in Jupiter's atmosphere followed the resumption of RTS data collection. During the wave structure observation, at 09:17 UTC on Oct. 10<sup>th</sup>, a little over five hours into the encounter sequence, internal processing of recorded PPR data accessed a stuck bit in Galileo's CDS memory (See Section 4.1),

causing the spacecraft to enter "safe" mode.

During the hours needed to restore critical systems spacecraft function (See Section 6), PPR observations of Jupiter and of Io's night side, approximately 20 hours of RTS data, and a six-hour fields and particles recording in the Io torus were lost. Because of the nature of the anomaly, all subsequent stand-alone PPR observations had to be removed from the sequence, resulting in loss of regional- and global-scale radiometry coverage of Io's day side. PPR ride-along observations were unaffected (see below).

The Galileo Flight Team, through a combination of efficiency and preparedness, was able to uplink a contingency encounter sequence, which began executing at 03:00 UTC on Oct. 11<sup>th</sup>. After 30 minutes of activities designed to match the actual state of the instruments and spacecraft to the expected

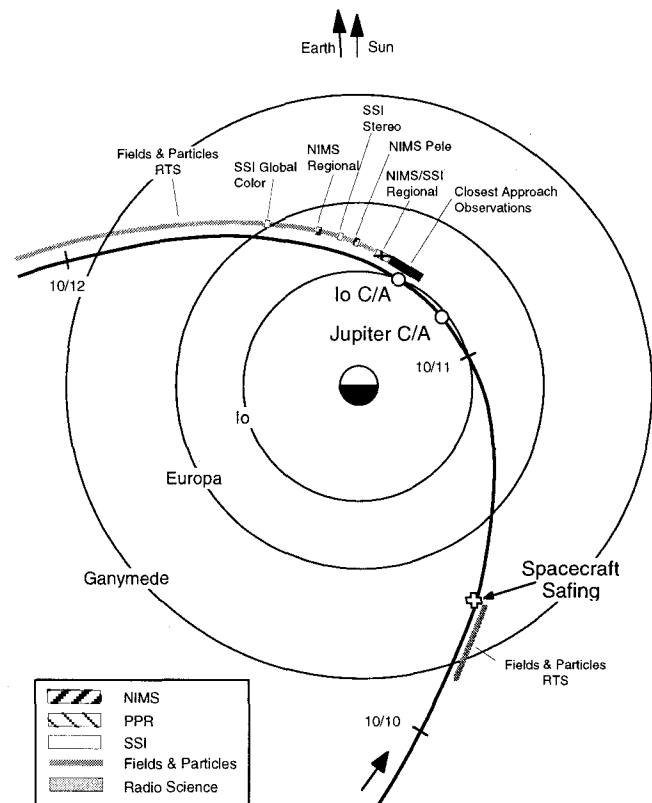


Figure 5a. Io 24 Encounter Trajectory

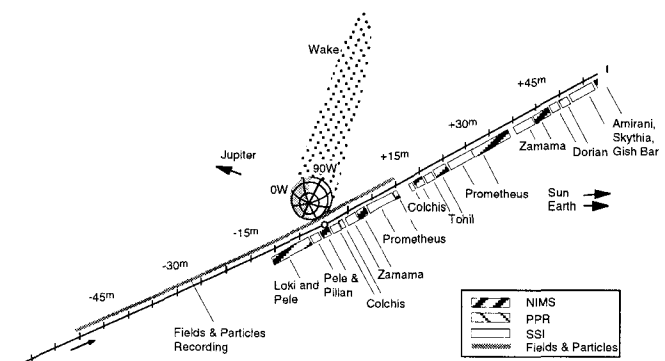


Figure 5b. Io 24 Flyby Geometry

state for Io encounter, Galileo resumed data-gathering activities with a 65-minute recording of high-rate fields and particles data (Figure 5b), which allowed these instruments to observe electromagnetic fields, radiation environment, and dust particle distribution in the close vicinity of Io and upstream of the circum-Jupiter flow of the Io torus plasma.

During the first half-hour of this observation, PPR “rode along” with the fields and particles observation, recording their data at the same time and obtaining high-resolution (56-13 km) radiometry data of the Loki hotspot. In a similar manner, PPR obtained ride-along data during many of the subsequent NIMS and SSI observations of other hotspots and features on the surface of Io (see below).

SSI obtained numerous high-resolution images of Io’s surface, with over 100 images taken of 10 targets at resolution better than 500 m (the highest resolution data obtained during the Voyager flybys). Targeted features included volcanic eruption centers such as Pillan Patera, Zamama, Prometheus, and Pele, and an attempt to capture the plume over Pillan at the highest-ever resolution (1.3 km). An image of the Pele volcanic center was taken over Io’s night side, revealing a glowing crack along one side of a caldera, where lava had recently been exposed to the surface. Other target features included regions containing several volcanic features (e.g., Amirani and Gish Bar) or some of the enigmatic mountainous features on the surface of Io, such as Colchis Montes, and Tohil Mons. Regional and global-scale images were taken, with regional coverage focused on obtaining the stereo pair to an image taken several months earlier, and a region near the terminator, where lighting conditions are optimal for analysis of Io’s topography. The global-scale images included a mosaic of best color images of the region from Loki to Pillan, and an observation of Io while in eclipse, showing the level of hotspot activity in the Pele hemisphere, as well as atmospheric airglow and auroral emissions.

During the two-hour period centered on closest approach, NIMS obtained IR spectral measurements of many of the same targets as SSI, either just before or just after the SSI observations. These include the volcanic centers at Loki and Pele (taken during darkness on Io), Pillan, Zamama, Prometheus, and Amirani, as well as the mountains at Colchis Montes, and Tohil Mons. In addition, NIMS obtained stand-alone data of Loki in darkness (shortly after PPR) at high resolution. As the spacecraft moved further from Io, NIMS obtained two regional maps, as well as observations of both the Pele and Pillan plumes (the latter in collaboration with SSI).

Prior to its Io 24 observations, the NIMS diffraction grating stuck in or near its initial position (See Section 5). As a result, all NIMS observations were restricted to specific wavelength bandpasses instead of being able to obtain a more continuous set of wavelengths. Although this anomaly limited possibilities for inferring composition, the resulting wavelength set was well suited for thermal measurements and for certain types of compositional measurements, including mapping of

SO<sub>2</sub> abundance. Moreover, the stuck grating meant that samples were repeated multiple times, decreasing radiation-related and other noise effects on the data.

The UVS instrument had targeted a number of objectives, including studies of Io’s composition and surface textures, searches for atomic species in the transient atmosphere, and observations of Io’s airglow while in eclipse. In addition, measurements of the Io torus were planned. As described in Section 5, UVS was turned off prior to the beginning of the Io 24 encounter due to problems with its grating encoder electronics. Real-time commands were sent after recovery of the spacecraft and passage through the high-radiation environment near perijove in an attempt to recover some UVS objectives. These commands did not improve the behavior of the grating, and no useful data were obtained. EUV observations consisted solely of Io torus monitoring. EUV gathered spectra for approximately the last day and a half of the encounter sequence.

Due to the memory anomaly (See Section 4.1), a non-standard strategy was used for playback. Most commonly, data are played back off the spacecraft tape recorder in the same order that they were recorded. However, there were concerns about playing back SSI images, since the affected region in memory was also used for SSI data during playback. Thus, SSI data were excluded from playback until the stuck bit was located and found to be outside the region of memory used for SSI processing.

Once SSI data began returning, problems with summation mode images quickly became apparent (See Section 5). One effect of the high radiation levels experienced during the flyby was to corrupt all of the images obtained in SSI’s hardware (in-camera) summation mode. Of 156 total frames of Io image data, 122 were obtained using summation mode and were affected by radiation-induced corruption. Despite the evidence of corruption and concern over whether the data could ever be reconstructed, it was decided to play back as much of these images as possible because of the unique nature of the data. Subsequent to their return, engineers at JPL were able to derive empirical methods for reconstructing the images. Of the corrupted images, 77 have been successfully reconstructed, and another 24 have been reconstructed over a significant portion of the frame, yielding approximately 135 frames of unique data of the surface of Io.

Another non-standard activity during the cruise period after the Io 24 encounter was RTS data collection by the fields and particles instruments. Less data were available on tape than had initially been planned, freeing up some downlink for RTS data. Approximately 13 days of RTS data were collected, from Oct. 19<sup>th</sup> through Nov. 1<sup>st</sup>. In addition, DDS data were collected continuously from Oct. 11<sup>th</sup> through Nov. 1<sup>st</sup>. The region thus covered, in the dusk sector of the magnetosphere, had been largely unexplored to this point.

## **7.2 Io 25**

The fourteenth satellite encounter of GEM occurred on

November 26<sup>th</sup> at 04:05 UTC, when Galileo passed over the south polar regions of Io (76.6 °S, 44.3° W) at an altitude of 300 km. The sequence of commands for the encounter was initially developed as a single load, beginning at 04:00 UTC on November 25<sup>th</sup> and ending at 23:30 on January 1<sup>st</sup>, 2000. The encounter portion of this sequence (i.e., the time during which data are recorded to the tape recorder, and prior to playback) was just under two days in length, beginning at 04:00 UTC on Nov. 25<sup>th</sup> and ending at 00:30 UTC on Nov 27<sup>th</sup>. With the exception of the near-polar location of the closest approach point, the geometry was similar to the previous flyby, with the spacecraft approaching on the night side of Io and upstream relative to flow of the Io torus plasma. Details of the geometry of the encounter and flyby, as well as the relative location of many of the observations are shown in Figures 6a and 6b.

Although the focus of this orbit's activities was Io, significant resources were also devoted to Europa science objectives. This encounter included a non-targeted flyby of Europa at an altitude of 8,633 km, at 16:29 UTC on November 25<sup>th</sup>. This flyby was the only opportunity in either Prime Mission or during GEM to view the Jupiter-facing hemisphere of Europa at sub-kilometer resolution, as well as a unique opportunity to obtain moderate-resolution coverage of the northern polar regions of Europa.

The encounter sequence began with the resumption of RTS observations by the six fields and particles instruments.

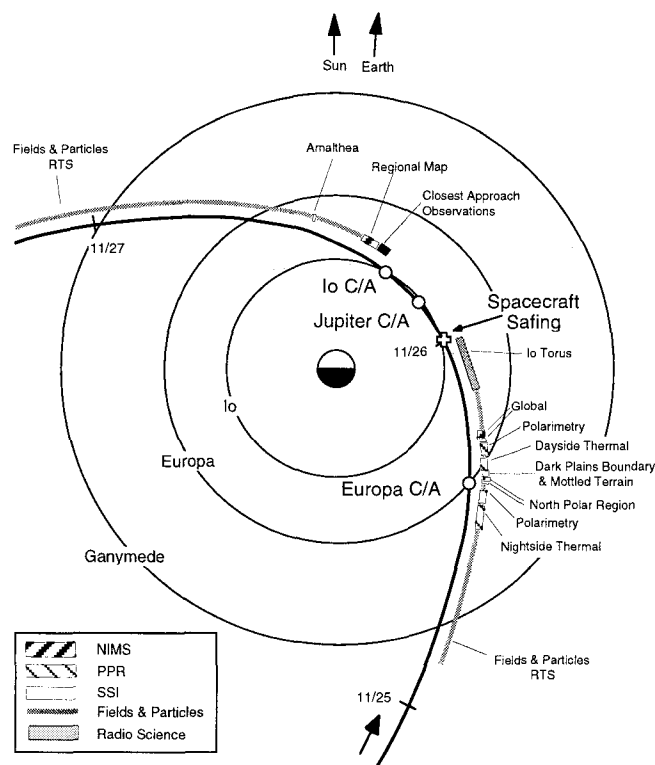


Figure 6a. Io 25 Encounter Trajectory

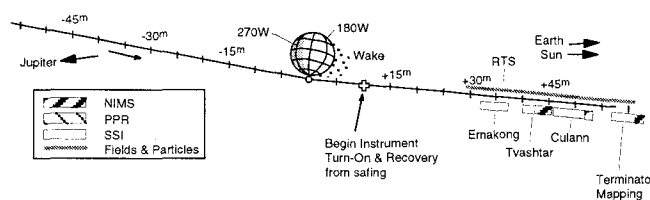


Figure 6b. Io 25 Flyby Geometry

Similar to the previous encounter, RTS data were to be collected for just under 2 days, beginning with the encounter sequence at approximately 16.5  $R_J$ , and ending at 00:00 UTC on Nov. 27<sup>th</sup>, at 16.3  $R_J$ . More than a day earlier, the dust detector instrument (DDS) began collecting RTS data on its own, beginning at 04:00 UTC on Nov. 22<sup>nd</sup>, and planning to continue through 00:00 UTC on Nov. 29<sup>th</sup>.

Approximately 10 hours after the start of the encounter sequence, Galileo began observations of Europa with PPR radiometry measurements of the night side of Europa, followed by PPR polarimetry measurements at high phase angle along the lit crescent of Europa. Additional PPR observations included a thermal map of Europa's sub-Jovian hemisphere and a set of low phase angle polarimetry measurements. The radiometry and polarimetry data are part of an observational campaign to characterize the thermal properties (e.g., thermal inertia) and small-scale surface characteristics (e.g., surface textures) of Europa.

During Galileo's closest approach to Europa, SSI observations included images of the north polar region of Europa, seen previously only at low resolution and unfavorable viewing angles, and regional-scale coverage of two regions in the sub-jovian hemisphere. Two hours after closest approach, SSI obtained a global-scale mosaic showing most of Europa's sub-jovian hemisphere. NIMS observations at Europa included coverage of the north polar region, moderate-resolution coverage (~20 km) of the region surrounding the sub-jovian point, full spectral resolution coverage of an equatorial band from 90°W through 320° W longitude, and a global-scale observation of the sub-jovian hemisphere. The NIMS grating remained stuck throughout the Io 25 encounter (See Section 5). Thus the improvements to NIMS thermal data and signal to noise and decreases to spectral coverage remained the same as in Io 24.

Subsequent to these Europa observations, the fields and particles instruments initiated a six-hour-long, high-resolution recording of the passage through the Io torus. The recording began at 21:06 on Nov. 25<sup>th</sup>, approximately four and a half hours after Europa closest approach, and seven hours prior to Io closest approach. During this span of time, the spacecraft would traverse the Io torus from 7.0  $R_J$  through perijove at 5.7  $R_J$  and back out to Io at 5.9  $R_J$  (1  $R_J$  = 71,492 km). Nearly two hours into this recording, PPR began a "ride along" observation, obtaining a global radiometry map of Io's night side. Near the end of the PPR observation, and halfway through the torus recording, the spacecraft entered safe mode and observations

were halted (See Section 4.2, Figure 6a).

Recovery efforts faced a number of significant difficulties. There was extreme time pressure, with the spacecraft only two hours from perijove and four hours from Io closest approach at the time of safing. Moreover, it was near 4:00 p.m. local time on a national holiday. Despite these difficulties, a prepared contingency sequence was modified (by removing the first hour's worth of observations, those within  $\pm 30$  minutes of Io closest approach) in order to allow time for sequence uplink and spacecraft and instruments configuration. It was then radiated to Galileo, and the spacecraft was restored to normal operations in time to allow for the last half of the planned Io observations (See also Section 6).

Several major science objectives went unfulfilled because of the anomaly. Among the most significant was the loss of fields and particles observation during the highest-priority period of  $\pm 30$  minutes of closest approach. The observation was to address the question of whether or not Io possesses an internally-generated magnetic field, and to what extent the observed magnetic signature of Io could be explained by electrical conductivity within the atmosphere and solid body of Io. This question was a primary driver of the polar geometry chosen for the flyby. Also lost were the highest-resolution remote sensing data of particular volcanic hotspots and other regions, including the south polar regions, the Emakong and Tupan volcanic features, and IR spectral data of the Prometheus plume.

Offsetting these losses were the spectacular data obtained as a result of the flight team's aggressive approach in recovering the spacecraft (Section 6). The resulting images and spectral maps allowed many of the remote sensing objectives for this encounter to be addressed. These data revealed new details of the Culaan Patera region, showed the relief at several of Io's unusual mountains and associated calderas, and yielded a high-resolution view of a bright lava flow which may be due to the flow of molten sulfur. In one series of images of the Tvashtar Region in northern Io, both SSI and NIMS obtained data of an actively erupting lava fountain (See PIA02545 in Appendix Section). This extremely dynamic event generated a curtain of lava that stretched for 20 km along a fissure and reached heights of more than 1 km above the surface. When such events occur on Earth, they commonly last for as little as a few hours to a day or two. Even considering the high levels of volcanic activity on Io, Galileo's capture of such an event was extremely fortuitous.

### 7.3 E26

The Europa 26 encounter marked the end of the Galileo Europa Mission and the beginning of a second mission extension, the Galileo Millennium Mission (GMM). The first satellite encounter of GMM occurred at 18:00 UTC on January 3<sup>rd</sup>, 2000, when Galileo passed within 351 km of the surface of Europa. The closest approach point was approximately 47° S, 276°W, slightly south and west of the prominent impact

crater Pwyll. The command sequence was developed as a single load, beginning at 23:30 UTC on January 1<sup>st</sup> and ending on February 20<sup>th</sup> at 04:00 UTC. The encounter portion of the sequence began at the same time as the overall sequence and was nearly four days in length, ending at 21:00 UTC on January 5<sup>th</sup>. Details of the geometry of the flyby and location of encounter observations are shown in Figure 7a and 7b. Only a very limited number of observations were made in this orbit. This was due to operational considerations including the decreasing period of Galileo's orbits (which necessitated more rapid development cycles for orbital sequences), a smaller workforce than in GEM, and a decrease in available downlink resources.

The encounter sequence began with the resumption of real-time science (RTS) data collection by the six fields and particles instruments. This survey of the inner magnetosphere began at 23:30 UTC on January 1<sup>st</sup>, at approximately 29  $R_J$  and continued until 02:00 UTC, January 5<sup>th</sup>, at  $\sim 15 R_J$  outbound. RTS data collection by DDS began nearly a day earlier, at 00:00 UTC on January 1<sup>st</sup>, and continued through 12:00 UTC on January 9<sup>th</sup>, at approximately 55  $R_J$ .

Recorded observations during the encounter were limited to (1) a 60-minute recording of fields and particles data centered on Europa closest approach, (2) high-resolution SSI images of selected targets near the terminator of Europa, (3) SSI images of three of the four inner moons of Jupiter (Thebe, Amalthea, and Metis), and (4) a joint SSI/NIMS observation

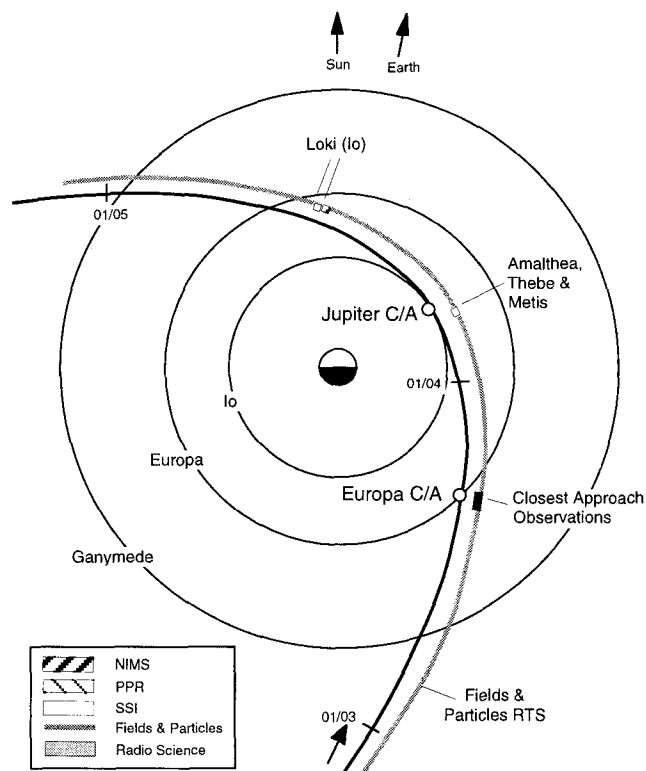


Figure 7a. Europa 26 Encounter Trajectory

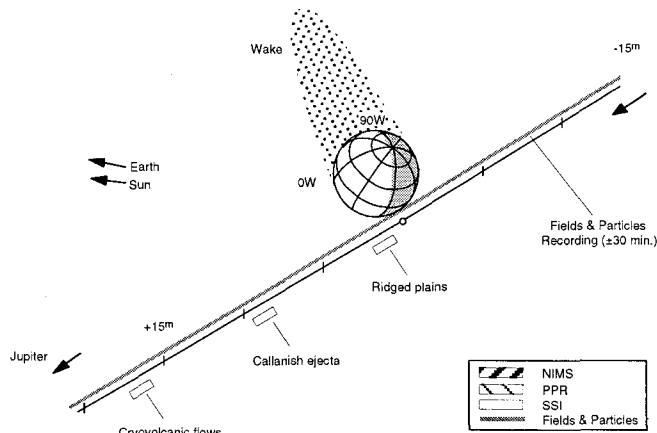


Figure 7b. Europa 26 Flyby Geometry

of the Loki region on Io.

The high-resolution fields and particles recording began at 17:30 UTC on January 3<sup>rd</sup> (Figure 7b). Approximately two minutes after closest approach, SSI began obtaining its images of Europa. By 18:17, imaging was completed, while the fields and particles instruments continued collecting recorded data until 18:30 UTC. SSI images were obtained at very high resolution (down to ~ 11 meters per pixel) and showed features relating to the question of sub-surface water inside Europa. Specific targets included low-sun-angle views of possible cryovolcanic flows, ejecta from the Callanish impact basin, and the point of intersection of two ridges.

The timing and geometry of the Europa 26 flyby were specifically designed to answer questions about the magnetic field signature of Europa. Flybys of Europa in both Prime Mission and GEM showed distinct changes in magnetic field magnitude and direction in the near vicinity of Europa. The data were ambiguous as to the source of this magnetic signature, and were basically consistent with the presence of either an internally-generated magnetic field (similar to Ganymede's or Earth's) or an *induced field*, generated by the effect of Jupiter's strong magnetic field on a partially conductive Europa. Since a subsurface, briny ocean was the most straightforward way to explain a conductive layer inside Europa, there was considerable interest in resolving this ambiguity.

The solution lay within the relative geometry of Europa and Jupiter's magnetic field. Because of the offset between Jupiter's rotational axis and its dipole field axis, the satellites of Jupiter cross the magnetic equator from north to south and back again each time Jupiter (and its magnetic field) rotates beneath them. While Europa is above the magnetic equator, the radial component of Jupiter's field points away from Jupiter; when Europa is below the magnetic equator, the radial component of the magnetic field points toward Jupiter. Until the Europa 26 encounter, the only useful data at Europa had been obtained in the northern lobe of Jupiter's field. By timing the encounter such that Europa was south of the magnetic equator during Galileo's flyby, data could be obtained which

would show whether or not Europa's magnetic signature was time-varying (indicating an induced field) or not (indicating an intrinsic, internally-generated field).

Following the Europa flyby, images of three of the four small inner satellites of Jupiter were obtained between 02:45 and 03:15 UTC on January 4<sup>th</sup>. These images were obtained within an hour of perijove and are the highest-resolution views of Amalthea, Metis, and Thebe that have been obtained to date. Eight hours later, with Galileo in a geometry favorable for observations of the Loki volcanic region of Io, NIMS and SSI obtained color images and spectral map data of this difficult-to-observe region located in the Jupiter-facing hemisphere of Io. Encounter activities ended with an EUV observation of the Io torus starting at 02:30 UTC on January 6<sup>th</sup> and ending at 03:00 UTC on January 8<sup>th</sup>. However, due to a sequencing error no data were obtained.

The loss of EUV data was caused by usage of an incorrect RTS format. EUV can place its data into the RTS downlink stream either by placing discrete commands to read its internal data buffer at specified times, or by selecting into the real-time data process. In the latter case, EUV's data buffer is read at a regular interval determined by the RTS format. Throughout most of Prime Mission and all of GEM, only the former method had been employed. The automated mode was used in the Europa 26 sequence, with RTS Format A. However, this format does not include EUV data processing capability, so no data were obtained. Subsequent use of the automated mode of RTS data collection utilized the correct RTS format and was successful.

The limited amount of recording during this encounter allowed for data obtained in the previous orbit to be carried over and played back along with newly-obtained data. Thus, the cruise period included playback of both Europa 26 and Io 25 data. Data carried over from the previous orbit included the majority of the fields and particles data recorded during passage through the Io torus, SSI data from the Culaan, Tvashtar, and Emakong regions of Io and from a global-scale observation of the Jupiter-facing hemisphere of Europa, and NIMS data from their regional- and global-scale observations of Europa and Io.

#### 7.4 I27

The Io 27 encounter marked the second flyby of the Galileo Millennium Mission (GMM). The spacecraft encountered Io at 13:46 UTC on February 22<sup>nd</sup>, 2000, approaching to within 198 km of the moon's highly volcanic surface. The sub-spacecraft point at closest approach was approximately 18°N, 202°W, in Colchis Regio, directly west of the active hotspot Zamama. The encounter sequence was developed as a single command load, beginning at 04:00 UTC on February 20<sup>th</sup> and ending nearly 5 days later, at 03:00 UTC on February 25<sup>th</sup>. Details of the geometry of the flyby and location of encounter observations are shown in Figures 8a and 8b.

This encounter represented an opportunity to target observations based on data obtained in the Io 24 and Io 25 flybys, but was also very downlink-limited. Solar conjunction occurred during the latter portion of the Io 27 cruise period. Because of both solar interference and the fact that the spacecraft was near its maximum range from Earth, telemetry rates are relatively low during such orbits. In addition, data obtained in the two previous Io encounters had allowed new questions to be raised and had demonstrated that we had only begun to sample the diverse landforms and processes shaping the surface, the transient atmosphere, and their interactions with the Io torus and Jovian magnetosphere. For all these reasons, observations were very strongly weighted toward the period of closest approach to Io. Approximately three-quarters of all the tape-recorded observations were obtained in a three-hour period beginning forty minutes before closest approach, with Io as the target in all of them.

A dearth of DSN tracking and the occurrence of a near-occultation of Earth by Jupiter meant that only two science observations occurred during the first two days of the encounter sequence. The first was the RTS survey of dust in the Jovian system by the DDS instrument. DDS observations began 16 hours prior to the start of the encounter sequence, at 12:00 UTC on February 19<sup>th</sup>, and continued through 00:00 UTC on February 29<sup>th</sup>. The second observation was obtained by tracking Galileo's radio signal during a near-occultation of the spacecraft by Jupiter, as the signal passed through the upper portions of the atmosphere in the north polar region.

One day after the start of the encounter sequence, real-time science (RTS) data collection was resumed by all the fields and particles instruments. The RTS survey of the inner magnetosphere began at approximately 04:00 UTC on February 21<sup>st</sup>, at 22  $R_J$ , and continued until 18:00 UTC, February 23<sup>rd</sup>, at ~20  $R_J$  outbound. The fields and particles instruments also obtained approximately four hours of high resolution data, from approximately three hours prior to Io closest approach (at 10:22 UTC on February 22<sup>nd</sup>) until 39 minutes after closest approach (at 14:25 UTC). Only three hours of the recorded data could be returned due to downlink limitations. However, the data did fill a gap in radial coverage of the Io torus caused by the spacecraft safings in the earlier Io encounters. The geometry of this flyby was similar to Io 24, but occurred at a different angle with respect to plasma flow and Io's wake (Figures 8b, 5b). This allowed for data to be obtained in a region of intense interactions between Io and co-rotating plasma, a region seen during the Io flyby nearly four years earlier.

PPR observations began more than eight hours before the torus recording, obtaining measurements of vertical wave propagation and structure in the lower stratosphere of Jupiter's atmosphere. All subsequent PPR observations were focused on Io. Galileo approached Io on the night side, allowing PPR to obtain a global map of thermal radiation and make high-resolution observations of the hot spots Loki and Daedalus.

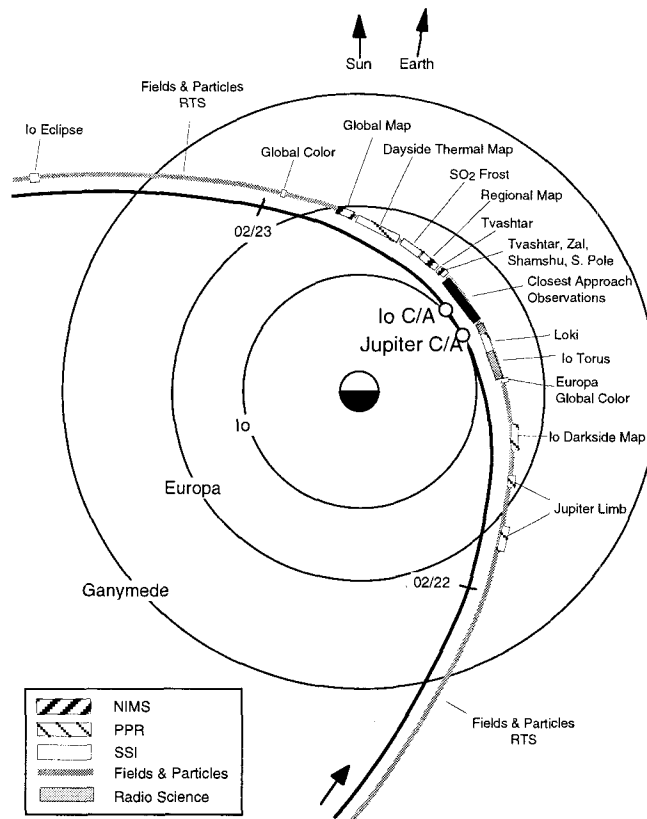


Figure 8a. Io 27 Encounter Trajectory

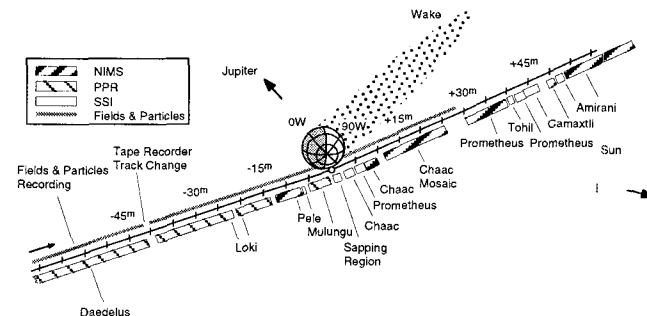


Figure 8b. Io 27 Flyby Geometry

Later, as Galileo passed over Io's sunlit hemisphere, data were obtained showing daytime temperatures of SO<sub>2</sub> frost deposits, as well as the global distribution of dayside temperatures. In addition, PPR obtained polarimetry data of the Mulungu Patera region, helping to fill in gaps in phase angle coverage in the overall mission data set for Io.

SSI observations were also heavily focused on Io. The only non-Io observation was a color image of Europa (Figure 8a) that filled in a longitude gap in color data coverage. Observations of Io included a mix of very high (~10 m/pixel) and moderate resolution (~100's of m/pixel) images, as well as global-scale images. Experiences from previous Io encounters showed that moderate resolution images taken at low-sun-angle conditions were extremely valuable for

establishing the basic shape and geology of features on Io. Moderate-resolution targets included the Tvashtar Catena region, where an active eruption was seen during the Io 25 flyby, as well as Zal and Shamshu Patera, the south polar region, Tohil Mons, and the Amirani eruptive center. High-resolution targets included the caldera at Pele (taken in darkness), the active lava flow front at Prometheus, and Chaac Patera, which became active in between the two previous Io flybys in 1999. Global-scale observations of Io included a global color image, used to detect any color or albedo changes in the surface over time, as well as long-exposure images of Io taken in eclipse. The latter images continued a campaign to look for changes in Ionian hot spots, measure their temperatures, and look for changes in visible emissions from Io's transient atmosphere.

NIMS observations for the encounter were exclusively targeted toward Io. Prior to closest approach and while over the night side of Io, data were taken over the Pele volcanic center down to 1 km/pixel resolution. On the day side, NIMS observed a number of key regions of Io in collaboration with SSI observations. These regions included the area near Chaac Patera, with its greenish "golf course" features, the Camaxtli hot spot, Prometheus, Amirani, and the Tvashtar Catena region. As Galileo receded from Io, NIMS also obtained a regional and a global scale observation. Such observations are useful for mapping hot spot distributions and looking for changes from orbit to orbit, as well as for obtaining maps of SO<sub>2</sub> distribution across the surface of Io.

In addition to the active remote sensing and *in-situ* observations obtained during the Io closest approach period, radio science measurements of Io's gravity field were obtained from Doppler shifts in Galileo's radio signal during the 20 hours centered on closest approach. These data are used to refine characterizations of Io's gravity field and to improve models for the structure of Io's interior.

The final observation planned for the encounter was a series of EUV scans across the Io torus and Jupiter. Because of EUV's spacecraft-fixed position, it can only observe targets which drift across its field of view. Io 27 represented the best opportunity to obtain EUV spectra of the torus since early in Galileo's Prime Mission. Unfortunately, these observations were interrupted by a spacecraft safing (See Section 4.3) due to a transient bus reset, and no torus data were obtained.

This safing event also had negative impacts to the return of Io data. The total available downlink for Io 27 was relatively sparse in comparison to other Io encounters, in part because it was a conjunction orbit. Loss of playback time to safing recovery was an additional impact. These considerations, along with the high science value of Io data already returned, led to the decision to carry some Io 27 data into the next orbit (See Section 7.5). This would limit the amount of tape that could be used to record data from the Ganymede 28 encounter, but judicious choice of tape recorder modes allowed for nearly all science objectives to be satisfied while using less tape.

## 7.5 G28

On May 20<sup>th</sup>, 2000 at 10:10 UTC, Galileo flew by Ganymede at an altitude of 809 km. At closest approach, the sub-spacecraft point was at approximately 19°S, 266°W, passing over the terminator and crossing Ganymede's orbit upstream of its magnetospheric wake. The encounter sequence was developed as a single command load, beginning at 10:00 UTC on May 17<sup>th</sup>, 2000 and extending until 23:00 UTC on June 13<sup>th</sup>. This unusually long encounter sequence was developed to support a 25-day long survey by the fields and particles instruments (see below) and is in keeping with the unusually long duration of the Ganymede 28 orbit, which lasts seven months. Details of the geometry of the flyby and location of encounter observations are shown in Figure 9a and 9b.

The encounter marked the beginning of the Cassini Phase of the GMM, so-called because of the planned collaborative observations of the Jovian system by Galileo and Cassini which will occur for a nearly four-month-long period centered on Cassini's closest approach to Jupiter on December 31<sup>st</sup>, 2000. Although this phase includes only two orbits (Ganymede 28 and 29) it will last for up to one year due to the increased period of Galileo's orbits. The primary science goals of joint Galileo-Cassini observations are to:

- Study how interactions with the solar wind affect the dynamics and structure of Jupiter's magnetosphere, including the Jovian auroral regions.
- Significantly improve understanding of the dynamics

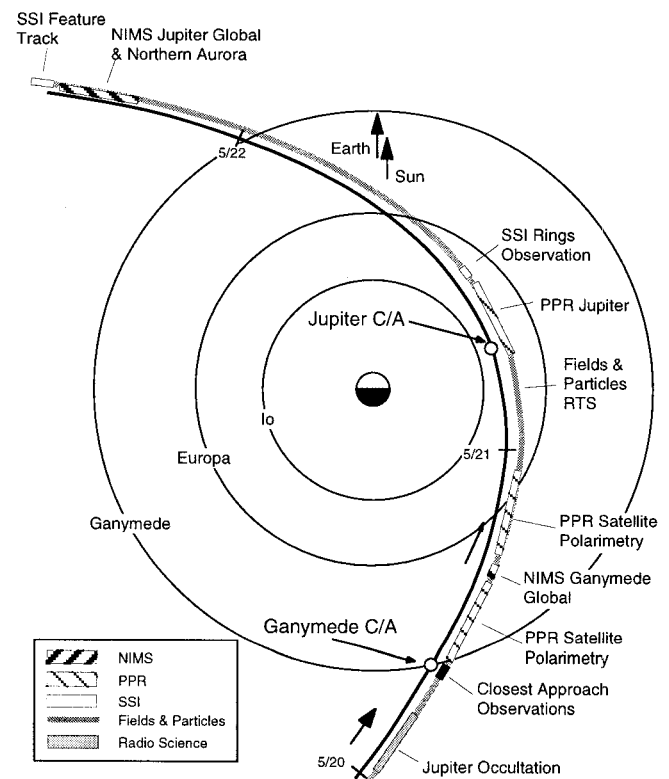


Figure 9a. Ganymede 28 Encounter Trajectory

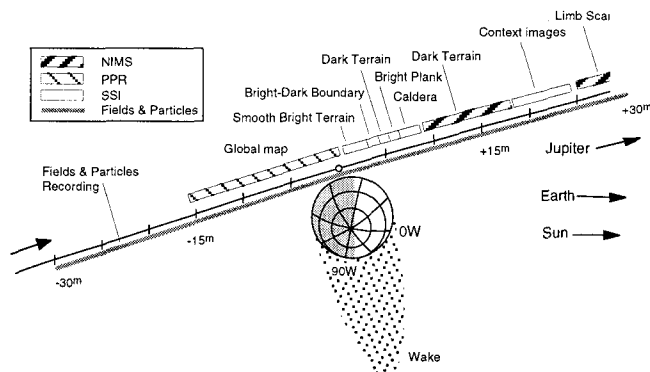


Figure 9b. *Ganymede 28 Flyby Geometry*

of Jupiter's atmosphere, particularly with regard to active storm regions.

- Observe Io while in eclipse in order to investigate airglow phenomena and monitor hotspot activity.
- Study the dynamics of Jovian dust streams using near-simultaneous measurements of a particular dust stream from both Galileo and Cassini.

In addition to these joint goals, there are several unique opportunities afforded to Galileo during this phase of operations. The primary science goals for stand-alone Galileo science are to:

- Study the dynamics of the largely unexplored dusk sector of the magnetosphere.
- Understand the dynamics of Ganymede's unique magnetosphere.
- Study key features at very high resolution to understand the relative importance of tectonism and volcanism in forming Ganymede's surface.
- Determine particle sizes in the various ring components of the Jovian ring system.
- Study the storm system dynamics represented by the recently-merged white ovals in Jupiter's atmosphere.

During the first day of the Ganymede 28 encounter sequence, data were obtained for only one science observation, the RTS survey by the DDS instrument. DDS observations began just 30 minutes prior to the start of the sequence, at 09:30 UTC on May 17<sup>th</sup>, and continued through 00:00 UTC on June 19<sup>th</sup>.

At 04:00 UTC on May 19<sup>th</sup>, the other fields and particles instruments began their RTS survey, which would last through the end of the encounter sequence on June 13<sup>th</sup>. The extended nature of this survey enables studies of the dusk sector of the Jovian magnetosphere, and provides new information on the transition regions between the magnetosphere and the solar wind. Unlike during Prime Mission, 24-hour coverage by the DSN for Galileo was not available. To prevent data gaps when downlink coverage was unavailable, extensive use was made of the "buffer dump to tape" process, in which temporarily buffered RTS data are written to tape for later playback. More than half of the survey data were dumped to tape and are being replayed during the July-October period.

The recorded observation by the fields and particles instruments was obtained during a 60-minute period centered on Ganymede closest approach, from 09:40 to 10:40 UTC on May 20<sup>th</sup>. In its near-equatorial pass, Galileo penetrated into the region where Ganymede's magnetic field is as strong as Jupiter's field, allowing Galileo to study the interaction region between the two magnetospheres. At closest approach, the PWS instrument obtained 30 seconds of high-rate recorded data to search for the occurrence of chorus emissions. Such emissions are characteristic of the Earth's magnetosphere and would indicate the presence of similar wave-particle interactions in Ganymede's magnetosphere.

In addition to fields and particles observations, the early part of the encounter also included two occultation experiments performed by the Radio Science Team. In the first, Galileo passed behind Jupiter's north polar region as seen from Earth, allowing the first atmospheric soundings of the north polar region, as well as ionospheric sounding of the northern auroral zone. In the second, the spacecraft was occulted by Ganymede, allowing observations of that moon's ionosphere.

PPR targets for the encounter included three of the Galilean satellites and the Jovian atmosphere. Near Ganymede closest approach, PPR obtained high-resolution radiometry data simultaneous with SSI images of specific targets (see below), followed by a global-scale observation approximately two hours later. Polarimetry data for both Io and Europa were obtained, as part of mission-long efforts to understand the Galilean satellites' scattering properties. PPR also obtained three sets of observations of Jupiter, a polarimetry measurement of the atmosphere along a north-south transect (for the first time since September of 1997), a set of high-resolution scans along the limb of Jupiter for studies of upper atmospheric wave propagation, and observations of the recently-merged white oval storm features.

NIMS observations were focused on Ganymede and Jupiter. The Ganymede flyby afforded NIMS the opportunity to significantly extend or improve existing regional- and global-scale coverage of Ganymede, and to perform a limb scan observation to search for direct evidence of a tenuous atmosphere at Ganymede. Planned Jupiter observations included a series of three global-scale maps covering a total of 360° of longitude, a series of 10 auroral observations taken over a 10-hour period, and a similar series of observations of the near-equatorial bright limb, designed to assess any variability seen in the equatorial bulge over a Jupiter rotation.

Significant cuts had to be made in the atmospheric observations due to the fact that NIMS was unable to use their nominal low-rate record mode (LPU). Although higher-speed record modes are available, their cost in tape usage is a factor of four greater. The LPU mode has been unavailable since Io 24 as a result of the same memory cell failure that caused spacecraft safing during that encounter (See Section 4.1). Prior to Ganymede 28, this difficulty had little impact to NIMS science. Most of the NIMS observations obtained since

the anomaly were of Io, where a high-rate record mode is used. Efforts to develop a software fix are making good progress as of early August, and it is hoped that LPU mode will be available to NIMS before the Ganymede 29 encounter in December.

Similar to NIMS, SSI observations heavily emphasized the opportunities at Ganymede closest approach and for Jupiter atmospheric observations. Ganymede observations were obtained during a 42-minute period beginning approximately 3 minutes after closest approach. During the first six minutes of this period, SSI obtained a series of images at very high resolution (~20 m/pixel) and with low-sun-angle conditions well suited to enhancing the topography of features. These images targeted features such as the contact between a region of bright terrain and a dark terrain unit and the intersection of two large ridges. Such features contain information about volcanic and tectonic processes that shaped Ganymede's surface, and their relative importance. Later images consisted of moderate resolution views to provide context for high-resolution images.

At Jupiter, SSI obtained a feature track observation of the Great Red Spot (GRS), in which three sets of images are obtained at intervals of one to several hours in order to observe cloud dynamics. This is the first such observation of the GRS by Galileo since the Ganymede 1 encounter nearly four years earlier. This encounter also afforded SSI the opportunity to image the Jovian ring system under conditions of low phase angle and relatively high tilt angle. Such observations allow for estimates to be made of the particle sizes in the main ring, the gossamer rings, and the halo, and permit a better look at wavelike features in the main ring that were detected in earlier observations.

Toward the end of the long encounter sequence, EUV was again able to observe the Io torus, taking data over a period of approximately 17 days, beginning on June 9<sup>th</sup> and ending on June 26<sup>th</sup>, 2000. During this long observation, EUV obtained data of the Io torus from dayside to nightside ansa, as well as spectra of the auroral region of Jupiter.

Ganymede 28 is a rich orbit for Galileo in terms of the amount of data that can be returned, primarily because of its long duration. To best take advantage of this capability, it was decided to carry over some of the image data from the previous bit-poor orbit, allowing additional valuable Io data to be returned. Playback of data after the thus began with the carried-over Io 27 data. As of early August, data from the Ganymede closest approach period is being returned. Playback will continue until late October.

The final planned observation is an RTS survey by the fields and particles instruments, which will begin in late October and continue through the Ganymede 29 encounter, until early February of 2001 (Figure 10). The purpose of this period of data collection is to perform joint magnetospheric observations with the complementary set of instruments onboard the Cassini spacecraft. Using both sets of instruments,

Galileo and Cassini will be able to obtain simultaneous measurements of the solar wind and the interior of the Jovian magnetosphere. This unique opportunity will permit scientists to begin to understand how the dynamics of the Jovian magnetosphere respond to changes in the solar wind.

## **8. New Scientific Discoveries**

### **8.1 Europa's Induced Magnetic Field**

Observations of Europa's magnetic field during Prime Mission revealed the presence of a significant magnetic signature. Two possible models for the source of this signature were proposed. One possibility was that the signature was due to an intrinsic magnetic field generated inside Europa, while the other possibility was that a time-varying field was being induced by the interaction between the Jovian field and a conducting Europa. Measurements obtained during Prime Mission and GEM were unable to distinguish between the two possibilities because they were obtained at times when Europa was at similar phasing relative to the Jovian field (i.e., Europa was either at or north of Jupiter's magnetic equator). The Europa 26 flyby was specifically timed to occur such that Europa would be south of Jupiter's magnetic equator.

Measurements obtained by the magnetometer conclusively demonstrated that Europa's magnetic field is created by an inductive response to the Jovian field, and is due to the presence of a conducting layer beneath Europa's surface.<sup>7</sup> The only plausible explanation thus far for such a conductor is a layer of liquid water (or a water-ice slurry) containing dissolved salts at concentrations at or above those in the terrestrial oceans. Models show reasonable fits to the data for layers at depths of order 100 km or less, and layer thicknesses of approximately 10-100 km. Data obtained by Galileo during its Prime Mission and GEM showed surface features, such as the iceberg-like features seen in chaos terrains, and numerous features thought to be due to ice volcanism. These features strongly suggested that liquid water was present at or near Europa's surface at some time in the past, but could have represented times as much as 100 million years ago. The magnetometer measurements are consistent with the presence of such a layer at the present time, and thus constitute some of the best evidence for liquid water inside Europa today.

### **8.2 Source of Jovian Dust Streams**

Recent findings by the DDS team have shown that dust streams emanating from the Jupiter system are related to the volcanic activity of the innermost Galilean satellite, Io.<sup>8</sup> Jovian dust streams are intense bursts of sub-micron-sized particles which are charged via interactions with UV light and then accelerated out of the Jovian system by Jupiter's magnetic field. They were first observed by the dust detector instrument on the Ulysses spacecraft during its 1992 flyby of Jupiter. Galileo's DDS also observed these streams for over a year prior to its arrival at Jupiter in 1995. Over the past four years

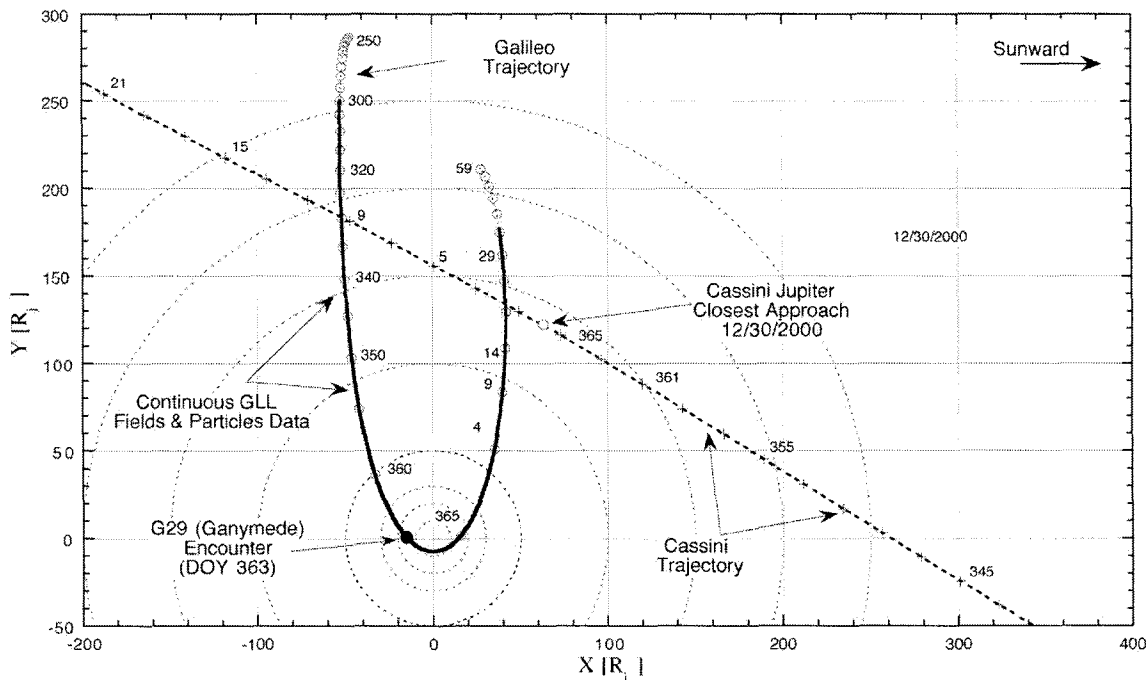


Figure 10. Galileo and Cassini Joint Observation Trajectories

of Jupiter observations, DDS has patiently collected data in order to constrain the source of these streams. Both Io and Jupiter's gossamer ring were considered to be potential sources for dust streams. Careful analysis of data collected during Galileo's tour<sup>8</sup> reveals peaks in dust activity which correspond with Jupiter's rotation (10 hours) and Io's orbital period (approximately 42 hours), demonstrating that the particles originate at Io and may reflect variations in volcanic activity.

### 8.3 Volcanic Processes at Io

The three Io encounters over the past year have yielded a wealth of information about the surface of Io and the processes that have shaped it, as well as the volcanic moon's interactions with Jupiter's magnetosphere. Initial analyses of data from the 1999 encounters with Io have only recently been completed, and data from the Io 27 encounter will continue to be returned by Galileo through at least September of 2000. Several of the most significant results of these early analyses are discussed below.

One of the most spectacular images obtained by Galileo (or any other planetary mission) was taken during the Io 25 flyby (See PIA02545 in Appendix Section) of a region of overlapping calderas in northern Io and referred to as the Tvashtar region. The image showed a crack running left to right, approximately 20 km long, as well as an associated white (overexposed) region. The white area is caused by hot lava, which was hot enough (and thus bright enough) to overload detectors in SSI's CCD array, causing "bleeding" of electrons and creating columns of saturated pixels in the image. The hot lava was being erupted in an event called a fire fountain. Such events occur when magma in a conduit or

crack nears the surface and is rapidly accelerated upwards as gas exsolves from the magma due to the decrease in pressure. Such events are seen in basaltic volcanoes on Earth and are extremely dynamic, typically lasting for a few hours to a day. Less commonly, numerous fire fountains form along a crack, creating a "curtain of fire" like the one seen at Tvashtar. Observations made in February, 2000, three months later, showed that volcanic activity had moved to the west, creating a lava flow over 60 km in length.

Galileo's images of the Prometheus region on Io have solved the mystery of that plume's apparent westward movement between the 1979 Voyager observations and the first Galileo observation in 1996. The Prometheus plume has been one of the most consistent features of Io since it was first detected during Voyager flybys of the Jovian system. Distant images obtained by Galileo throughout Prime Mission and GEM consistently showed the same height, shape and optical properties as compared to Voyager images. However, these same images showed that the plume was now originating from a point 75 to 95 km west of its Voyager-era location.<sup>9</sup> SSI images and NIMS thermal measurements obtained in the Io flybys have shown that the Prometheus region contains a large caldera, which appears to be the source for an extensive flow field stretching nearly 100 km to the west. Thermal measurements reveal hot material just south and west of the caldera, and a larger hot region to the west at the end of the flow field. The smaller hot spot is at the approximate location of the Voyager-era plume, while the western hot spot coincides with the current source region of the plume.<sup>10</sup> The smaller, eastern hotspot is thought to be due to magma erupting just to the south of the caldera. It then enters a series of lava tubes,

which insulate the high-temperature magma, and allow it to flow westward, ending up in the western hotspot, where new flows are being emplaced.<sup>9</sup>

These observations dramatically altered our understanding of how plumes such as Prometheus are generated and maintained. Prior to Galileo's observations, plumes were thought to be most analogous to terrestrial geysers, where groundwater circulation near a subsurface magma body has created an extensive plumbing system, and eruptions occur at a single, stationary conduit. Plumes are suggested to arise in a very different way. As lava flows out over sulfur-rich deposits on Io, the heat causes the cold, solid S and SO<sub>2</sub> beneath to melt and then vaporize. Kieffer et al.<sup>11</sup> suggest that vaporized S and SO<sub>2</sub> then erupt through rootless conduits. This type of explosive eruption has been studied in both Hawaii and Iceland, and occurs on Earth when molten lava interacts with surface or near-surface water. Thus, the source of the Prometheus plume is currently in the region where new flows are being emplaced, but was much nearer to the caldera during the Voyager era.

In addition to causing changes to the surface, Io's volcanic activity is also responsible for its tenuous atmosphere and the materials that make up the Io torus. Data from the magnetometer indicate that the uppermost atmosphere (the exosphere) varies significantly with time, and have demonstrated one mechanism by which molecular ions (e.g., SO<sub>2</sub><sup>+</sup>) are transported from near-Io space and into the Io torus. Data from flybys in 1995, 1999, and this year have all shown intense cyclotron wave activity in the vicinity of Io. Such waves are produced under conditions where newly-created ions are picked up by the Jovian field and accelerated to join the Io torus plasma. Galileo's measurements have shown that the region characterized by these waves extends much further than expected—up to at least 20 Io radii from Io. The expected size of this interaction region was only 2 Io radii, consistent with Io's extremely tenuous atmosphere.

The large size of the interaction region can be explained by the transport of ions away from Io. Transport occurs when exospheric particles (e.g., SO<sub>2</sub>) become ionized and are accelerated away from Jupiter by electric fields associated with the magnetosphere. Normally, such ions would be trapped by the magnetic field within a narrow range of distances. However, near Io they can encounter neutral (not yet ionized) particles, undergo charge exchange, and exit the region on ballistic trajectories. Such particles are then re-ionized by solar UV photons causing the more-distant cyclotron waves.<sup>12</sup> This is one way in which materials produced in volcanic plumes are spread throughout the Io torus.

The detections of cyclotron waves have also shown that Io's exosphere and surroundings vary considerably with time. On each Io flyby, the intensity of the waves has changed, as have the characteristic frequencies, indicating changes in composition. In 1995, only SO<sub>2</sub><sup>+</sup> ions were detected. In late 1999 (Io 24) and during the Io 27 flyby both SO<sub>2</sub><sup>+</sup> and SO<sup>+</sup> were

seen. The measurements also indicate different concentrations of ions with time, and reveal compositional inhomogeneities in the near-Io regions.<sup>12</sup> These changes are most likely related to changes in plume activity and the composition of plume gases with time.

## **9, Future Plans**

### **9.1 Ganymede 29**

As of this writing, the Ganymede 29 encounter is still in the planning stages. This is the last of the presently approved flybys for the Galileo Millennium Mission (however, See Section 9.2). This possibly ultimate encounter will occur on December 28, 2000, 08:26 UTC, at an altitude of 2321 km. The encounter sequence will be forty days long, begin on December 27, 2000, and end on February 5, 2001. Figures 11a and 11b provide details of the G29 encounter observations.

The fields and particles instruments will record continuously for approximately 60 minutes around close approach. In addition, they will obtain approximately forty days of continuous real-time science data as Galileo makes a transition from the inner magnetosphere, through the magnetopause and bow shock regions, and into the solar wind. This survey is one of three such transits (the other two occurring in Ganymede 28) which allow for the exploration of the afternoon and dusk sectors of the Jovian magnetosphere.

The remote sensing instruments will be targeting Jupiter, all four Galilean satellites, and the rings. Jupiter observation targets will include measurements of hot spots, aurora, the Great Red Spot wake, the north temperate zone, a global observation, and a feature track. Io observations will include monitoring for volcanic activity, polarimetry, eclipse imaging, global observations, and observations of the Io sodium cloud. The Europa observation will be a NIMS global measurement. The Ganymede observations will include an attempt to image the aurora, eclipse measurements, regional mapping, global mapping, and polar cap measurements. The Callisto observation is a global NIMS measurement. And finally, there will be a pair of ring observations by the SSI.

### **9.2 Post GMM**

As of this writing, the plans for spacecraft activities after Ganymede 29 are still under development. The Galileo Project and NASA Headquarters are trying to determine the future of the spacecraft. Multiple options are available for this time frame, and one possible scenario is shown in Figure 12. This option would follow up on many key Io questions not answered by previous Galileo data. Such questions include: whether Io's magnetic field is intrinsic (i.e., due to a geodynamo like the Earth's) or induced (indicating a conducting Io); the quantitative value of heat flow, which can tell us about the details of the tidal heating mechanism; how Io's mountains are formed and why many of them are associated with calderas; how and why volcanism produces such high temperature and

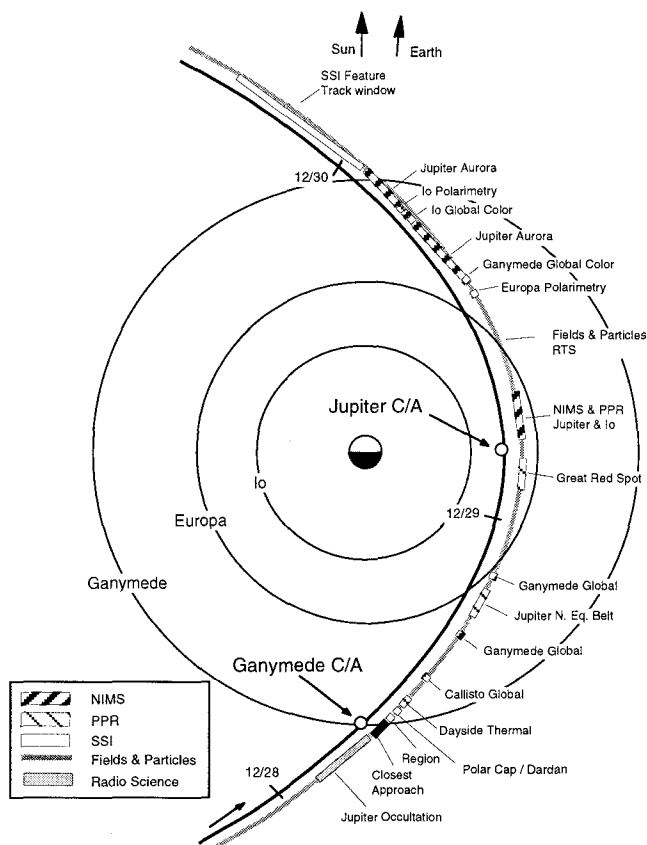


Figure 11a. Ganymede 29 Encounter Trajectory

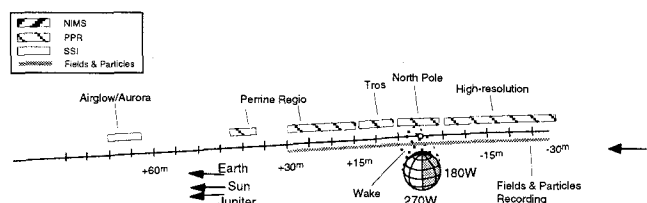


Figure 11b. Ganymede 29 Flyby Geometry

occasional high volume eruption; and what are the detailed eruption mechanisms of Io's plumes.

This option comprises Callisto 30, Io 31, Io 32, and targeting to an additional Io 33. Both Io 31 and Io 32 are polar passes conducive to studying Io's magnetic field. The following paragraphs represent merely one possible trajectory, for one option. As no final decisions have been made, the described science observations are possibilities, and not firm targets.

### 9.2.1 Callisto 30

The sole Callisto encounter of this extension option would occur on May 25, 2001, 11:24 UTC, at an altitude of 123 km. Possible Callisto observations and measurements could include observations of Asgard and Valhalla craters, stereo imaging of a domed crater, and Bran crater. Other observations could include Io volcano monitoring, global scale observations of Ganymede to fill gaps in previous

coverage, and Jupiter atmosphere observations to characterize 5-micron hot spots

### 9.2.2 Io 31

The first Io encounter of this extension would be a north polar pass on August 6, 2001, 04:59 UTC, at an altitude of 200 km. This would be an opportunity to characterize the source of Io's magnetic field, whether induced (like Europa's) or internally generated (like Ganymede's). There would also be significant remote sensing opportunities for the North Polar Region. Possible Io observations could include global night-side mapping, images and spectral mapping from specific hot spots (Loki, Pele, Pillan, Isum, Tvashtar, Prometheus), and global color maps. Other observations could include views of Lofn and Heimdall craters on Callisto to try and pin down relative ages and morphology, and Jupiter atmospheric observations to measure propagation speed of mesoscale waves.

### 9.2.3 Io 32

The second Io encounter of this extension would be a south polar pass on October 16, 2001, 01:26 UTC, at an altitude of 190 km. This would represent a second opportunity to determine the source of Io's magnetic field, and provide further unique Io remote sensing opportunities over the south pole. Possible Io observations could include views of Loki (including on the terminator), Telegonus scarp, the high southern latitude region, Emakong, Tupan, Chaac, Gish Bar, Shamash, and Prometheus. Other observations could include views of the outside edge of the gossamer ring to study the terminus, and Jupiter atmospheric hot spot measurements.

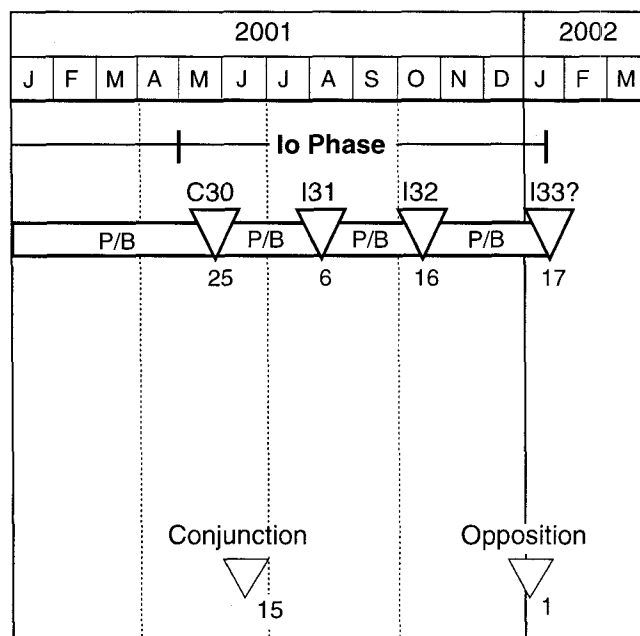


Figure 12. Possible 2001 Operations Timeline

### **9.2.4 Io 33**

The last Io encounter of this extension would occur on January 17, 2002, 14:09 UTC, at an altitude of 100 km. This encounter is designed to be flexible and provide the basis for any further spacecraft activities in 2002. This would not necessarily be a science data-taking encounter, but if further plans allow for it in 2002, this flyby could provide a unique opportunity to obtain high-resolution views of regions seen at moderate resolution by Voyager in 1979.

### **10. Summary**

At the 50<sup>th</sup> IAF Congress, the first of the Io encounters for GEM (Io 24) was days away. The GEM team had many concerns about being able to deliver at least one good Io encounter without the spacecraft failing. In the end, the team (and the spacecraft) came through with flying colors, aided by all of the preparations and analysis to be ready for failures. The problems that had to be overcome were not the specific ones analyzed or prepared for, but the team adapted what they knew to the real situation. The essential element of all the operations recoveries, as well as the successful planning and development of the science observations was teamwork.

This was teamwork not only within the current flight team, and between the investigator teams and the flight team, but teamwork between the Galileo Project and the Deep Space Network and other missions. The quick recoveries were only possible because of the ground stations being ready when needed, and other missions allowing the station time to perform the needed recoveries.

### **11. Acknowledgments**

The success of Project Galileo is due to the efforts of a large number of people, all of whom deserve acknowledgment for their contributions. Special recognition is due the members of the Galileo Team, both for GEM and GMM, who have kept this tremendous success going despite significantly reduced resources and some extra challenges in operating the spacecraft.

Very special thanks are due to Tiffany Chiu for her expert job of editing, layout, assembly and production. Somehow, even with the best of intentions the time available for her to do this gets squeezed as we try and get the latest information in. Also thanks to Olen Adams, Shadan Ardalan, and Paul Fieseler.

And the team operating the Galileo spacecraft today would like to offer a special thanks to the team members of the past. The hard work of the designers and initial operators of the Galileo Project gave the present operations staff the ability to deliver the world class science described in this paper.

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process, or service by trade name, trademark, manufacturer, or otherwise, does not constitute or imply its endorsement by the United States Government or the Jet Propulsion Laboratory, California Institute of Technology.

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